Preprint
UCRL-JC-142284

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This article was submitted to
1998 Applied Superconductivity Conference, Palm Desert, CA,
September 13-18, 1998

June 1, 1999

This work was performed under the auspices of the United States Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Critical Current Measurements on Large Conductors of Niobium-Titanium/Copper Cable Embedded in an Aluminum Stabilizer

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Abstract---**Insertion of a flat, Rutherford type, cable of NbTi/Cu composite strands into a rectangular profile of high purity aluminum is an established method of superconductor fabrication for certain applications. Although this processing scheme has numerous advantages it produces a composite material whose properties are difficult to predict with precision. The *BABAR* detector magnet currently being tested at the Stanford Linear Accelerator Center, uses high-purity aluminum stabilized superconducting cable. The performance of the superconductor is dependent on the quality of the fabrication of the composite conductor. Here we present measurements of the critical transport current of *BABAR* production grade conductors up to 10 kA, and at fields up to 10 T. Data are related to production variables, compared to estimates from simple models, and evaluated with respect to design specifications.**

I. INTRODUCTION

A new detector called *BABAR*, has been designed and constructed at the Stanford Linear Accelerator Center (SLAC). The superconducting magnet sub-systems use high-purity aluminum (HP-Al) stabilized composite superconducting cables. To verify performance, tests of the current transport characteristics were performed on full-scale conductors at the National High Magnetic Field Laboratory (NHMFL). The large size and high current carrying capability of the conductor is well suited for characterization in the 13 T split-solenoid test station of NHMFL's Large Magnet Component Test Facility. The test facility allows testing of the conductors under simulated operating conditions. These tests verified conductor performance and have provided unique data to aid in the understanding of the characteristics of HP-Al stabilized composite conductors.

II. BACKGROUND

The design of HP-Al stabilized conductors must take into account conductor degradation due to processing variables such as cabling, roll forming, and co-extrusion, as well as the integrity of the stabilizer/superconductor interface bond. The critical current of the as-fabricated superconductor has been measured previously on samples extracted from production grade conductors by chemically etching away the aluminum matrix [1]. The prior test results of the cable showed that the critical current exceeds the design critical current specification: Ic (B = 2.5 T; T = 4.2 K) = 12.68 kA. Th lowest critical current measurement on short samples wa 14.25 kA. The tests reported here, of the as-fabricate composite conductor samples, were performed to eliminat concerns about the influence of sample preparation and tes methodology.

Manuscript received Sept. 14, 1998.
This work was supported in part by NSF Grant No. 9527035 and in part by Stanford Linear Accelerator Center.

III. CONDUCTOR DESCRIPTION

The conductor is composed of a NbTi/Cu fla superconducting cable (Rutherford Cable) that is embedde in a rectangular channel of high purity aluminum (HP-Al) using a co-extrusion process. In order to have a fiel homogeneity specified by the *BABAR* experiment, the curren density in the winding is graded: lower in the central regio and higher at the ends. The gradation is obtained by usin conductors of two different thickness: 8.4 mm for the centra region and 5 mm for the ends. Both 20 mm wide conductor are composed of a 16 strand Rutherford cable stabilized b pure aluminum. Table I describes the strands, the Rutherfor cable and the full-scale conductor characteristics. Th conductors are supplied by Europa Metalli (Fornaci di Barg –Italy). The co-extrusion processes were carried out a ALCATEL SWISS CABLE under assistance of ETH Zurich.

IV. TEST PROCEDURE

The tests are conducted using the 13 T split-solenoid tes station of NHMFL's Large Magnet Component Test Facility The key components of the test station are the split-solenoi superconducting magnet (150 mm bore, 30 mm by 70 mn radial access port, 100 mm length uniform field region) an the laboratory's main DC power supply configured to delive 200 V and 12 kA. The split-solenoid magnet test facility i described elsewhere [2]. Four separate conductors from fou production lots were tested. The analysis procedure used t interpret the data for only one sample (no.7) at one applie field (8 T) will be reported here.

Straight conductor lengths (approx. 900mm long) fron production lot material are bent at mid-length around mandrel to produce a hairpin sample. The sample is inserte into the 30mm by 70mm radial access port of the spli solenoid magnet (Fig. 1); the orientation is such that th applied magnetic field is perpendicular to the sample' current flow and parallel to the wide face of the conductor The samples are attached to a structural/electrically insulatin sample holder and current leads are soldered to the top end of the sample. The current flow through the sample i

TABLE I
SUMMARY OF SPECIFICATION FOR STRANDS, RUTHERFORD AND FULL CONDUCTOR

Component	Characteristic	Value
Strand	NbTi	Nb 46.5 +/- 1.5 wt % Ti
	Filament size	< 40 µm
	Twist pitch	25 mm
	Cu/NbTi ratio	> 1.1
	RRR	Final >100
	Wire diameter	0.8 mm ± 0.005
Rutherford	Transposition pitch	< 90 mm
	Number of strands	16
	Final size	1.4 x 6.4 mm2
Conductor	Al-RRR	~1500
	Dimensions:	
	Thin conductor	(4.93 x 20)±0.02 mm
	Thick conductor	(8.49 x 20)±0.02 mm
	Rutherford-Al bonding	> 20 MPa
	Al/Cu/NbTi ratio:	
	Thin conductor	23.5:1.1:1
	Thick conductor	42.4:1.1:1
	Edge curvature radius	> 0.2 mm

directed such that Lorentz forces tend to compress the sample onto the G-10 sample holder. The current is supplied through 12 kA vapor cooled leads to flexible NbTi cables with copper block terminations that are soldered directly to the aluminum jacketed sample.

The relatively short, U-shaped sample is positioned in the magnet such that the U shape of the sample is in the high field region. The 4.2 K tests are performed with a constant background field (for each data set) while the test sample current is ramped monotonically (Rate = 50 A/s) and sample voltage (tap spacing is 100 mm) is recorded.

V. TEST RESULTS

The results are twofold: first the tests confirm an effective electrical joint between the HP-Al stabilizer and the superconducting cable and secondly they verify superconductor performance including both critical current and index, under simulated operating conditions.

The early portion of the typical voltage versus current trace show the inherent characteristics due to the current distribution in the composite conductor (Fig. 2). When the superconductor to resistive transition occurs, power-law dependence is observed. The detailed shape of the trace depends upon intrinsic superconductor performance, self-field effects, and current sharing by the HP-Al stabilizer, which can be modeled as follows. Measurements of V vs. i for single wires in an external applied field B_a are observed to have power law dependence and the specification of the critical current $i_c\ (B_a)$ is done consistently with a voltage criterion V_0 and an index n according to:

$$V(i) = V_0\left[\frac{i}{i_c(B_a)}\right]^n, \tag{1}$$

If N wires are combined in a cable, a simplified expectation of the V-I characteristic might be

$$V(I) = V_0\left[\frac{I}{I_c(B_a)}\right]^n, \tag{2}$$

where

$$I_c(B_a) = Ni_c(B_a). \tag{3}$$

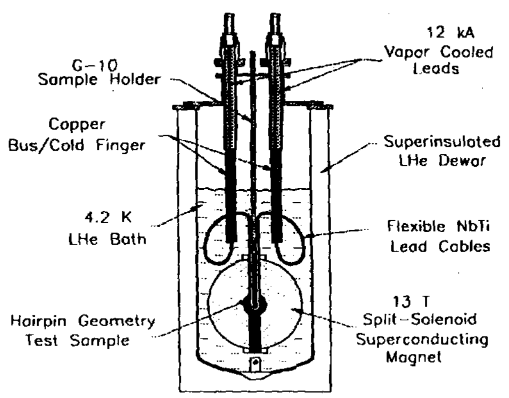

Fig. 1. Sectional schematic of 13 T magnet showing test sample position.

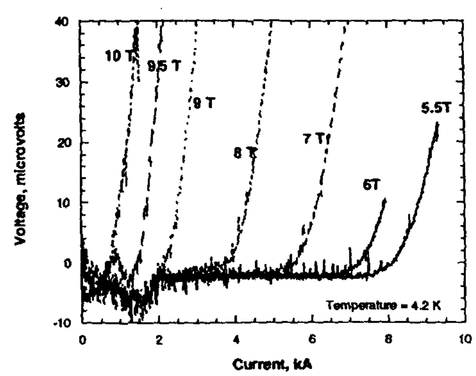

Fig. 2. Voltage vs current data at various applied fields for tests of sample 7.

However, the appropriate field B_t to be considered in the evaluation of a large, high-current conductor is the worst-case combination of applied field B_a and maximum self field B_s, i.e.

$$B_t = B_a + B_s(I), \tag{4}$$

which modifies the critical-current *criterion* according to [3]

$$I_c(B_t) = I_c(B_a)\left(\frac{B_a}{B_t}\right)^{0.4}\left[\frac{B_{c2}(T) - B_t}{B_{c2}(T) - B_a}\right]. \tag{5}$$

The self-field for the present conductors has been estimated to be approximately

$$B_s = 0.084 \times 10^{-3} I_{sc}, \tag{6}$$

where I_{sc} is the current inside the superconductor cable. The critical field at 4.2 K was taken to be about 10.4 T.

In the case of conductors with a large fraction of high-conductivity stabilizer shunting the superconductor, the transfer of a portion of the total current to the stabilizer according to the following also modifies the trace:

$$V_{sc} = V_0\left[\frac{I_{sc}}{I_c(B_t)}\right]^n = V_{stab} = V(I_t), \tag{7}$$

$$I_{stab} = \frac{V_{stab}}{R_{stab}}, \tag{8}$$

and

$$I_t = I_{sc} + I_{stab}. \tag{9}$$

The above discussion defines a fitting procedure in which $i_c(B_a)$ and n are the fitting parameters, thus giving a direct comparison between the measured V-I traces for the cable with stabilizer and those that might be expected on individual strands.

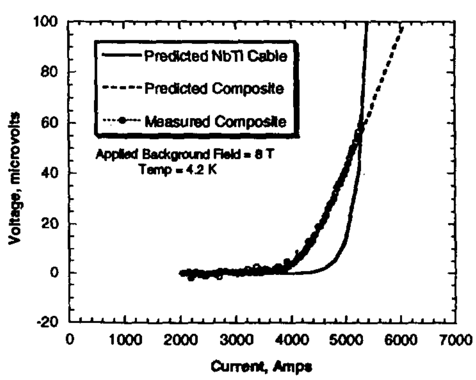

Fig. 3. The relationship between measured data and predicted for sample 7 at applied background field of 8 T.

Fig. 3 shows the excellent agreement between the test data of the full-scale conductor at 8 T, and the curve generated by the predictive equation for the full-scale conductor. The good agreement between measured and predicted data is observed for all the tests, establishing confidence that the effects of the HP-Al and self-field have been quantified. Also plotted in Fig. 3 is a curve of the expected performance of the Rutherford cable without HP-Al stabilizer. The curve is predicted using the measured data and eliminating the now quantified effects of the HP-Al and the self-field. This is the defining curve that provides the critical current and index of the as-processed Rutherford cable. Applying a 1e-4v/m voltage criterion to the curve results in a critical current of 4.45 kA at 8 T. The index of the cable is relatively low (23) for NbTi and may need to be studied more carefully to determine the reason for this. For reference purposes the results of the test on sample 7 are extrapolated to the BABAR magnet design operating field of 2.5 T. The extrapolation is based on well-known empirical relationships for NbTi [3] The extrapolation yields a relatively high critical current (23 kA) for the superconductor at 2.5 T. This value exceeds the prior estimate (14.2 kA) for the conductor, obtained in short sample tests [1].

VI. CONCLUSIONS

Full-scale production-grade conductors for the BABAR detector magnet have been successfully tested under simulated service conditions to provide engineering performance data. The critical current of the cable shows little degradation due to processing.

Analysis of the data demonstrates that conductor performance is consistent with our understanding and the properties of a HP-Al stabilized conductor are predictable with a high degree of certainty.

Based on our understanding of the present data for stabilized composite conductors, we suggest that current margins for the magnet are even higher than might be expected from previous tests of extracted cables.

ACKNOWLEDGEMENTS

The authors would like to thank J. Kenney of NHMFL for his technical expertise in sample preparation and G. Wend for his assistance with the tests.

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[2] L.T. Summers, R. P. Walsh, and J. R. Miller, "A facility for th characterization of the critical current of superconductors as a function of strain and magnetic field" IEEE Transactions on Applie Superconductivity, vol. 5 (2), pp. 1896-1899, 1995.

[3] Any of a number of commonly used relations allow quite adequa projections of NbTi critical current vs field and temperature. We choose use one from the computer program GANDALF, an analysis code for forc cooled conductors marketed by Cryosoft, 5, rue de la Belette, F-017 THOIRY, France.